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CROSS SECTIONS FOR THE FORMATION OF ^{114m}In AND ^{116m}In ON BOMBARDMENT OF CADMIUM BY DEUTERONS

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Abstract—Cross sections for ^{114m}In and ^{116m}In production by (d, xn) reactions on natural cadmium were measured by the stacked foils activation method. The results are compared with the maximum cross sections estimated from other published studies.[1–3] Thick target yield for Cd (d, xn) ^{114m}In reactions were determined for different irradiation times and as a function of deuteron energy.

INTRODUCTION

HISTORICALLY, chemists have investigated nuclear reactions by measuring the formation cross sections of specific product nuclides. Because of the small number of product atoms formed in most nuclear reactions, the yields of radioactive nuclides are usually measured. Much information has been obtained by the use of light projectiles.

Cross section data are useful in different fields of science and technology: these are prerequisite (i) when working in the field of charged particles activation analysis in order to predict both expected sensitivity and possible interferences; (ii) for development work on radionuclide production by means of charged particle bombardment; and (iii) the data are most useful in order to reliably predict residual radioactivity levels within acelerator facilities.

Deuteron bombardment of Cadmium leads to the production of ^{114m}In and ^{116m}In by (d, xn) reactions. In the work reported here, excitation functions for the production of ^{114m}In and ^{116m}In have been determined with deuterons up to 27.5 MeV on Cadmium targets. Irradiations were carried out on the 60 inch synchrocyclotron of the Argentine CNEA. The product nuclides were measured by gamma spectrometry with a Ge(Li) detector. Excitation functions for these reactions have not previously been reported. Thick target yields for ^{114m}In production are also presented in this paper.

EXPERIMENTAL

Irradiations

Stacks of natural cadmium foils were exposed to the synchrocyclotron deuteron beam.[4] In each case the target stack was thick enough to stop the 27.5 MeV deuteron external beam.

Thin target foils were placed between aluminum foils of known thicknesses. Since the ^{27}Al $(d, \alpha p)$ ^{24}Na excitation function is well known[5], the radioactive isotopes yield from cadmium, relative to ^{24}Na yield in the aluminum foils, allows us to obtain the absolute cross section values in reactions resulting from deuteron irradiation of cadmium.

The range-energy relationships of Williamson, Boujot and Picard[6] for cadmium and aluminum were used to determine the energies of the deuteron particles incident upon each cadmium target in the stack.

Uncertainty in the particle energy values for each data point arises from the energy spread of the incident deuteron beam as well as from energy straggling. The latter is about 0.5 MeV for the foil in which the deuterons had been slowed down to 16 MeV.[7] Maximum uncertainty in the incident beam energy was estimated to be less than 1%.

Counting

The productions cross sections were measured by the activation method.[8] After bombardment, gamma ray spectra of each foil were measured with a high resolution Ge(Li) detector coupled to a multichannel pulse height analyser.

Spectrometer calibration allowed for both gamma energy and photopeak intensity measurements. Absolute detection efficiency was determined using calibrated sources of known activity.

The values of gamma rays used for the detection and measurements of ^{114m}In ($T_{1/2} = 54$ min) were 189.90 and 1097.10 keV respectively. Data were taken at time intervals suitable for half life measurements for nuclide identification.

After each photopeak was recorded, the number of counts per unit time were obtained following Wasson's method.[9,10] Relative activities corresponding to the final irradiation times were calculated from decay curve extrapolations.

Values of detector absolute efficiency, as well as decay scheme data,[11,12] were used to convert peak count rate reading into nuclide activities.

Foil thicknesses and deuteron flux together with measured activities were used to calculate cross sections for ^{114m}In and ^{116m}In production.

Uncertainties in the cross section values were obtained by propagating in quadrature the contributions from peak analysis (including counting statistics) and decay curve analysis, absolute detector efficiencies, disintegration schemes, target thicknesses and deuteron flux.

No corrections were made either for the energy spread at each foil resulting from foil thickness variations, or for deuteron energy losses at preceding foils.

Losses of reaction products by recoil were assumed to be negligible.

RESULTS AND CONCLUSIONS

Let several isotopes of a given element yielding the same radionuclide be submitted simultaneously to charged particle irradiation.

The linear expression of σ

$$\sum_{i}^{n} \frac{a_i\sigma_i}{A_i} = \sigma_p \frac{\sum a_i}{\bar{A}} = \frac{\text{Act.}}{P\cdot\phi\cdot N_{\text{Av}}} \tag{1}$$

allows us to evaluate the respective contributions of the different nuclear reactions cross sections (σ_i) using Lange and Münzel's systematics.(1)

$\bar{A}$ is the average atomic weight

$$\bar{A} = \frac{\sum A_i a_i}{\sum a_i} \tag{2}$$

where A is the atomic weight, and a_i is the isotopic abundance of the target nuclides involved in the residual nuclei production, σ_p is the production cross section, P is the target weight, ϕ is the particle flux, N_{Av} is the Avogadro number and Act. is the radionuclide activity.

Values proportional to the cross sections for ^{114m}In production measured during this work are shown in Table 1 and plotted in Fig. 1 as a function of deuteron energy, E_d.

To evaluate the contribution of the possible ^{113}Cd (d, n), ^{114}Cd $(d, 2n)$ and ^{116}Cd $(d, 4n)$ reactions, the shapes of the excitation functions given by Lange and Münzel(1) are drawn as dashed lines in Fig. 1. Threshold energies given by Keller, Lange and Münzel(13) are indicated on the same graph.

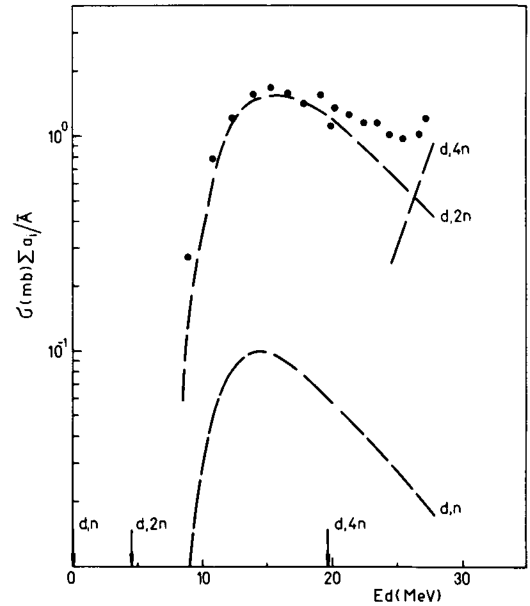

FIG. 1. ●●●●● $\sigma(mb)\Sigma a_i/\bar{A}$ for ^{114m}In.----, shapes of the excitation functions by Lange and Münzel.(1)

TABLE 1. CROSS SECTIONS

^{114m}In		^{116m}In	
E_d (MeV)	σ_p(mb) $\Sigma a_i/\bar{A}$	E_d (MeV)	σ (mb)
27.3	1.187 ± 0.08	22.9	189.6 ± 19
26.4	1.006 ± 0.09	22.0	333.4 ± 30
25.5	0.954 ± 0.09	21.0	329.9 ± 31
24.5	1.006 ± 0.09	19.9	374.6 ± 38
23.5	1.126 ± 0.08	18.8	462.2 ± 45
22.5	1.126 ± 0.07	17.7	525.2 ± 51
21.4	1.242 ± 0.08	16.5	632.1 ± 60
20.3	1.320 ± 0.09	15.2	551.7 ± 56
19.2	1.517 ± 0.10	13.9	633.6 ± 61
17.9	1.388 ± 0.10	12.5	547 ± 51
16.7	1.564 ± 0.10	11.0	498.6 ± 49
15.4	1.647 ± 0.10	9.2	226.6 ± 24
13.9	1.522 ± 0.10		
12.4	1.189 ± 0.08		
10.8	0.776 ± 0.07		
8.9	0.271 ± 0.04		

The absolute cross sections for (*d*, *n*) and (*d*, 2*n*) reactions can be obtained from the curves evaluated in this way by correcting for the ratio of atomic weight to isotopic abundance of the target nuclide involved (a_i/A_i).

Figure 2 and Table 1 display the ^{116}Cd (*d*, 2*n*) ^{116m}In excitation function. It includes the contribution of 2.16 s isomeric state due to the decay of the shorter lived precursor.[11,12] The solid line in Fig. 2 is the excitation function for this reaction given by Lange and Münzel's[1] systematics.

Absolute cross section values for ^{114m}In and ^{116m}In formation as calculated from our readings and corrected for isotopic abundance and atomic weight, were confronted with the maximum cross sections estimated from the work by Münzel and coworkers;[1–3] good agreement was found.

The thick target yield for ^{114m}In ($T_{1/2} = 50$ d.) production was calculated by numerical integration of the experimental cross section values obtained in the present work (Fig. 1, Table 1) using the methods of Lange and Münzel[1] and of Svoboda.[14] Values for energy intergration ranges are listed in Table 2. Saturation activity is the produced activity in thick targets when irradiation

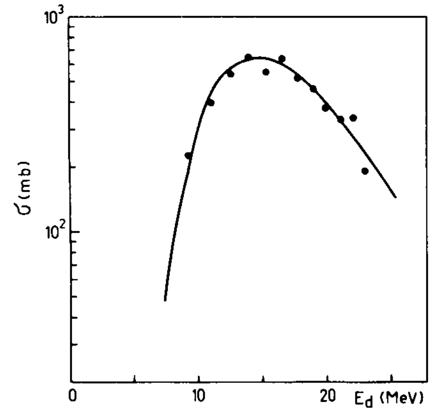

FIG. 2. ●●●●●, ^{116m}In excitation function.

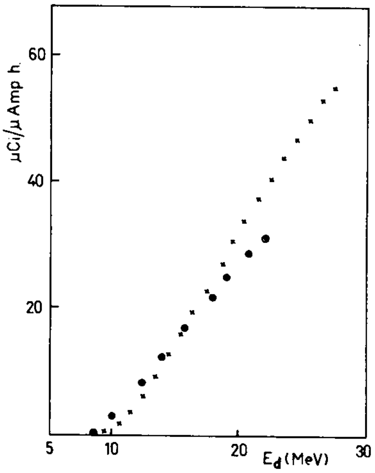

FIG. 3. × × × ×, Thick yield for ^{114m}In production; ⊙⊙⊙⊙, Data from Dimitriev *et al.*

TABLE 2. ^{116m}In THICK TARGET YIELDS

Range energy	Thickness of the target	Production cross section	Saturation activity	Σ Saturation activity	$\Sigma A_t/10$	ΣA_{1h}
(MeV)	(mg/cm^2)	(m.b.)	($\mu Ci/\mu A$)	($\mu Ci/\mu A$)	($\mu Ci/\mu A$)	($\mu Ci/\mu Ah$)
27.5–27	27.8	276.4	3.338×10^3	9.5634×10^4	6.404×10^3	5.52×10^1
27–26	54.9	236.6	5.641×10^3	9.2296×10^4	6.181×10^3	5.33×10^1
26–25	53.4	222.5	5.161×10^3	8.6655×10^4	5.803×10^3	5.00×10^1
25–24	51.9	236.6	5.333×10^3	8.1495×10^4	5.457×10^3	4.71×10^1
24–23	50.4	250.6	5.486×10^3	7.6162×10^4	5.100×10^3	4.40×10^1
23–22	48.8	267.0	5.659×10^3	7.0676×10^4	4.733×10^3	4.08×10^1
22–21	47.3	283.4	5.822×10^3	6.5016×10^4	4.354×10^3	3.75×10^1
21–20	45.7	309.2	6.137×10^3	5.9194×10^4	3.964×10^3	3.42×10^1
20–19	44.1	339.6	6.505×10^3	5.3057×10^4	3.553×10^3	3.06×10^1
19–18	42.5	339.6	6.269×10^3	4.6552×10^4	3.117×10^3	2.69×10^1
18–17	40.9	337.3	5.991×10^3	4.0283×10^4	2.698×10^3	2.33×10^1
17–16	39.2	372.4	6.341×10^3	3.4291×10^4	2.296×10^3	1.98×10^1
16–15	37.6	384.1	6.273×10^3	2.7950×10^4	1.872×10^3	1.61×10^1
15–14	35.9	372.4	5.807×10^3	2.1677×10^4	1.452×10^3	1.25×10^1
14–13	34.2	334.9	4.975×10^3	1.5870×10^4	1.063×10^3	9.16×10^0
13–12	32.5	285.7	4.034×10^3	1.0895×10^4	7.296×10^2	6.29×10^0
12–11	30.7	227.2	3.029×10^3	6.8613×10^3	4.595×10^2	3.96×10^0
11–10	29.0	171.0	2.154×10^3	3.8318×10^3	2.566×10^2	2.21×10^0
10–9	27.1	105.4	1.241×10^3	1.6782×10^3	1.124×10^2	9.69×10^{-1}
9–8	25.3	39.8	4.375×10^2	4.3755×10^2	2.930×10^1	2.53×10^{-1}

time is $t > 3T_{1/2}$. It ought to be kept in mind that for thick target results, isotopic abundance was assumed as $\Sigma a_i = 0.487$. Our results are shown as a plot of yields vs deuterons energy in Fig. 3. Comparison with the work of Dimitriev *et al.* (15) for ^{114m}In yield when irradiating thick cadmium metal targets, shows that our yields are higher a higher deuteron energies, probably due to the method used in each case.

In the literature there are no data on the yields of the nuclear reactions forming ^{116m}In by means of high energy deuterons.

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